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MATERIALS AND TECHNIQUES FOR MODEL CONSTRUCTI(

David A. Wigley

Kentron International, Inc.
Hampton Technical Center
Hampton, VA 23666

Applied Cryogenics and Materials (Subcontractor)
Consultants, Inc.
New Castle, DE 19720

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MATERIALS AND TECHNIQUES FOR MODEL CONSTRUCTION

by
D A.Wigley
President, Applied Cryogenics and Materials Consultants, PO Box 765, New Castle, De 19720, USA
Director, Cryogenic, Marine and Materials Consultants
17 Bassett Wood Drive, Bassett
Southampton, SO2 3PT, England

SUMMARY

The problems confronting the designer of models for cryogenic wind tunnel models are discussed with particular reference to the difficulties in obtaining appropriate data on the mechanical and physical properties of candidate materials and their fabrication technologies The relationship between strength and toughness of alloys is discussed in the context of maximising both and avoiding the problem of dimensional and microstructural instability. All major classes of materials used in model construction are considered in some detail and in the Appendix selected numerical data is given for the most relevant materials The stepped-specimen programme to investigate stress-induced dimensional changes in alloys is discussed in detail together with interpretation of the initial results The methods used to bond model components are considered with particular reference to the selection of filler alloys and temperature cycles to avoid microstructural degradation and loss of mechanical properties

1 INTRODUCTION

The advent of large cryogenic wind tunnels such as the National Transonic Facility (NTF) at the NASA Langley Research Center has created many challenges for the designer of models Optimization of the choice of material and fabrication techniques calls for fine judgment as many of the properties required are near the limits attainable with state-of-the-art technology Furthermore, in many cases improvements in one direction seem inevitably to be accompanied by losses in others Thus, for example, the material has to have a yield stress high enough to carry the imposed aerodynamic loadings, yet be tough enough to operate safely at cryogenic temperatures It has to be capable of being fabricated using available machining and joining techniques to give a model with a precisely known shape and a high quality surface finish which is able to retain dimensional stability during thermal cycling between ambient and its cryogenic operating temperatures. It has to be either intrinsically resistant to, or capable of being protected from, corrosion and degradation and, if it is to be of maximum use as an aerodynamic test facility, it has to be furnished with a complex array of orifices, tubes, sensors, heaters and other components needed for data gathering While many of these requirements have been familiar to generations of experimental aerodynamicists, it is the high Reynolds number requirement and in particular, the added cryogenic dimension that that has raised the designers' challenge to its present level

Some idea of the way information on the many factors involved in the design and construction of such models may be generated, stored and transmitted is illustrated schematically in Figure 1 At the conceptual stage the constraints set by the aerodynamic, aeroelastic and instrumentational requirements require the input of data contained in the various locations shown in the "Information Sources" box Further, more detailed, information is needed at the next stage when a general specification and design study is undertaken These include materials properties, information on shaping and joining technologies, as well as the cost and availability of candidate materials When fabrication of a specific model is undertaken, some information on the experience gained should start to flow back via feed-back paths to enhance the cumulative knowledge on both successful and unsuccessful techniques and materials used. Once the model has been put into service, further feed-back should enable its performance and degradation to be monitored Modifications or the adoption of alternative configurations should also provide valuable opportunities for data feed-back Finally, once a model has reached the end of its useful life, some form of post-mortum examination would allow comparison of the initial model design requirement with its subsequent performance Unfortunately much useful knowledge is often lost to the technical community as a whole when pressure of work, or a change of responsibilities, prevents adequate technical documentation of both successful and unsuccessful models

Many sources of data will need to be tapped to provide the breadth and depth of information required if models for cryogenic wind tunnels are to be fabricated efficiently Some information on the appropriate cryogenic technology is available in references 1-4 & 22 However, designers often experience considerable difficulty in finding the data they need, partly due the fragmented location of the available information, but also due to the specific nature of the problem Accordingly, research and development programs have been set up to investigate those areas of technology where information is most urgently needed Three particular topics being studied at NASA Langley Research Center are. (1) Toughness Enhancement by Grain Refinement, (2) Bonding and Filler Materials and (3) Dimensional Stability and Machining-Induced Deformation in Candidate Materials for Model Fabrication The author has been closely involved in the latter program and much of the material contained in this paper has been generated or collated under this NASA supported program Experience generated from other models in conventional as well as cryogenic wind tunnels should be supplemented with that from other relevant technologies For example, some of the data generated by the requirements of the nuclear fusion power generation program for very large superconducting magnets could have a direct bearing on the cryogenic model program The rationalization and collation of relevant information from these diverse sources would be of considerable benefit to those involved in the design, fabrication and use of models in cryogenic wind tunnels, particularly if it were to be collated in a " Handbook of Cryogenic Wind Tunnel Model Technology"

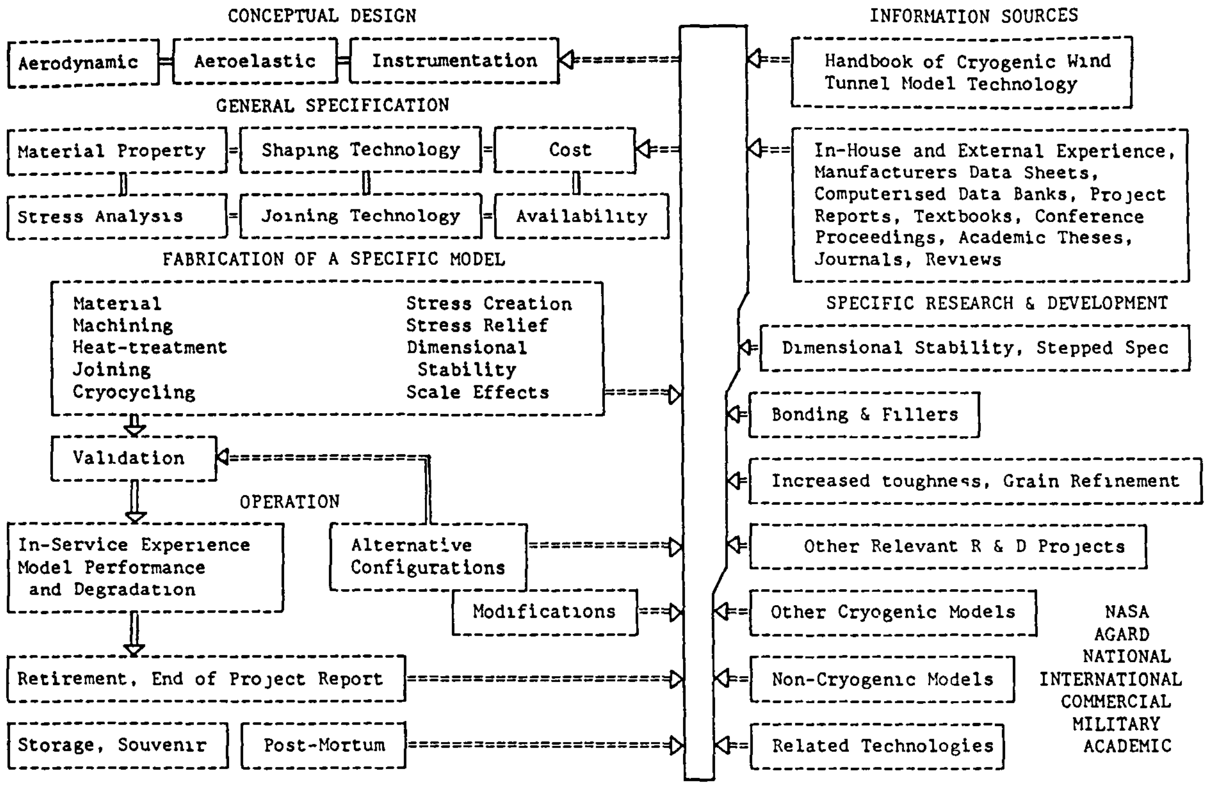


Figure 1 Schematic Representation of Information Transfer and Feedback Paths

2. FUNDAMENTAL CHARACTERISTICS OF METALS

2 1 Relationship between Strength and Toughness

The need for high strength while still retaining adequate toughness for safe operation severely limits the range of alloys that can be considered for the construction of models for large, pressurised cryogenic wind tunnels. The minimum yield stress considered acceptable for Pathfinder 1, the lead model for the NTF, is 1030 MPa (150 ksi) at 77 K (-320 F) This is not, in fact, a high stress level and the fracture toughness requirement of at least 93.5 MPa $\sqrt{m}$ (85 ksi $\sqrt{in}$), or a Charpy V notch Impact Energy of 34 J (25 ft-lbs) is not excessively cautious. However, applied together these two design requirements combine to narrow drastically the range of candidate materials. Basically, this is because most metallurgical techniques that increase the yield stress also bring about a decrease in fracture toughness. Furthermore, as the critical flaw size in a structure is related to the crack size factor, $(K_{Ic} / \sigma_y)^2$, an increase in yield stress without a corresponding increase in fracture toughness will lower the resistance of the material to unstable, low-energy crack propagation. This toughness-versus-strength trend for structural materials is well illustrated in Figure 2, as modified by Rush (Ref 31) from Toblers original (Ref 22). Most materials fall between the two trend lines, those at the upper boundary having the highest toughness for a given yield stress It should, however, be noted that these optimum properties are often not shown in the particular product form delivered for model fabrication Considerable effort is under way to produce materials having properties which lie above the upper trend-line of Fig 2 and there are two different basic approaches to this objective:

- Increasing Strength without Loss of Fracture Toughness as in the high nitrogen and high manganese stainless steels.

- Increasing Fracture Toughness without Loss of Strength in ferritic steels by the use of multiple stage heat-treatments through the austenite /austenite + ferrite phase transformation region.

Significant toughness improvements have been achieved by Rush (Ref 19) in 9% Nickel, HP 9-4-20 and 18Ni 200 maraging steel using this second approach

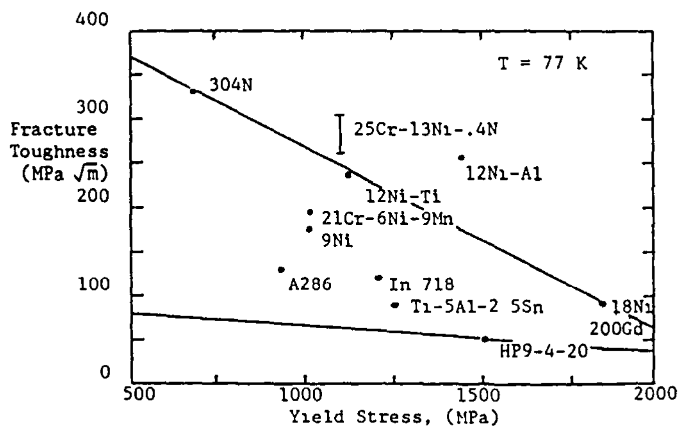


Figure 2 Toughness-vs-Strength Relationship

2.2 Dimensional Stability

In order to meet the minimum acceptable toughness requirements a number of precipitation-hardened stainless steels have to be heat-treated to a lower strength condition and it has been found that this can lead to dimensional instability. There are two basic mechanisms that can cause such instability:

- metallurgical structural instability in which one phase transforms partially or fully into a second phase which has a different crystal structure and volume.
- deformation due to the creation, or relief, of unbalanced induced or residual stresses

Stress-induced dimensional changes will be considered further in section 4 The occurrence of severe dimensional instability in a model first came to light in 12% airfoil made from 15-5PH stainless steel and tested in the 0.3-m Transonic Cryogenic Tunnel at NASA LaRC. A post-testing co-ordinate check showed a 0 002 in decambering of the aft airfoil section (6 in chord) and a 0 006 in. bow over an 8 in span Investigation showed that the material had been heat-treated to the H1150M condition in order to achieve a Charpy impact energy in excess of the required minimum of 25 ft-lb Table 1 shows manufacturers data on the relationship between condition, impact energy, tensile strength and contraction during the heat-treatment cycle, to which we have added comments on the structure and cryocycle stability. It can be seen that relatively little contraction is associated with the H900, H1025 and H1100 heat-treatments as these do not alter the martensitic structure of the material. The H1150M heat-treatment is accompanied by a much larger contraction as some martensite is transformed to austenite and it is the presence of this austenite than gives the material its improved toughness and impact energy. This austenite is, however, only metastable and low temperature cycling, machining or other forms of deformation trigger off a partial transformation back to martensite which is accompanied by a volume expansion In an asymmetric section such as an airfoil, and where the effect of machining would be more pronounced in thinner sections than in the thicker parts, the volume changes show up as warpage (Ref. 25)

Table 1 15-5PH Stainless Steel Stability Data (Ref 8)

Condition	77 K Charpy V Impact E (J)	Contraction H T -R Temp (%)	Cryocycle Stability	300 K UTS (MPa)	Structure
H900	-	0.045	-	1310	martensitic
H1025	2 7	0 053	good	1069	m/s
H1100	4 7	0 09	-	966	m/s
H1150	-	0 22	-	931	m/s + aust
H1150M	44 8	0 343	poor	793	m/s + aust

The energy required to trigger off the austenite to martensite transformation (an instantaneous shear, not a nucleation and diffusion-controlled growth mechanism) is probably provided by differential contraction during thermal cycling. Large temperature gradients would encourage such transformation, as would rapid temperature changes, and thus is is the rate of cooling and warming and the number of cryogenic cycles that determine the degree of transformation, rather than the length of time held at a particular temperature. Rapid changes of section would also exaggerate the problem as larger temperature gradients, and hence higher thermal stresses, are set up across thicker sections In the case of the 15-5PH airfoil the dimensional changes continued over many tens of thermal cycles, the incremental change becoming gradually smaller as the amount of metastable austenite transforming decreased. As, however, the toughness decreased progressively in step with the austenite transformation, there was no point in continuing to cycle the model to achieve dimensional stability as its toughness would then become unacceptably low In other, more stable, materials where some dimensional instability has been created by machining-induced stresses, it is possible to achieve effective metallurgical and dimensional stability be carrying out a few cryocycles prior to finish machining, providing that significant stresses are not re-introduced at this stage.

3 REVIEW OF ALLOYS USED FOR MODEL CONSTRUCTION

3.1 Austenitic Stainless Steels

3.1.1 AISI 300 series

The face-centered-cubic structure of the AISI 300 series stainless steels is rendered more or less stable at and below room temperature by the presence of austenite stabilizers such as nickel, manganese, carbon and nitrogen The 20% nickel present in type 310 makes it particularly stable, but it has the lowest yield strength of the 300 series. In the leaner grades, particularly the readily available 304 and 304L grades, the total concentration of austenite stabilizing elements may not be high enough to prevent some transformation to martensite, with its consequent volume change. This change can be induced thermally by lowering the temperature below the Ms (martensite start) temperature, or by mechanical deformation at temperatures below the Md (martensite deformation) temperature, which is usually a few hundred degrees higher than the Ms. These temperatures may be calculated from equations given in Ref. 12 if the composition of the alloy is known However, it is only the high-nitrogen versions of the 300 series that are likely to be strong enough for use for cryogenic models and these are some of the most stable members of the series Of particular interest are alloys such as that developed for the Japanese Atomic Energy Research Institute (JAERI) fusion reactor program which set a target of 1200 MPa for the 4 K yield strength, together with a 4 K Charpy impact energy of 100 J. A 25Cr-13Ni- 4N alloy, YUS 170, developed by Nippon Steel (Ref 20) has achieved this 4 K goal and its 77 K yield strength of 1130 MPa and a Charpy V energy of 243 J make it highly attractive for highly stressed cryogenic wind tunnel models

One feature common to almost all of the austenitic stainless steels is their ability to become sensitized if they are held for a significant time in the temperature range between 590 and 920 C (1100-1700 F). This is due to the precipitation of carbides and sigma phase at the grain boundaries and it has two particularly deleterious effects on the material At room temperature the main effect is to cause "weld-decay", a liability to inter-granular corrosion brought about by the loss of chromium adjacent to the grain boundaries Of more significance for cryogenic applications is, however, the serious loss of toughness at liquid nitrogen temperatures due to the ease with which fracture can be nucleated and

propagated in a low energy mode in the precipitate-laden grain boundaries. Unfortunately, airfoil models are frequently cooled through this sensitizing temperature range after post-machining, stress-relieving heat-treatments at 1000 C (1900 F) or during brazing. Should sensitization occur it can be removed by reheating to 1000 C and then cooling rapidly through the sensitizing temperature range This is, however, difficult to achieve with large, thick sections in a vacuum oven One common method of preventing sensitization is to specify one of the "weld-stabilized" grades such as the titanium bearing AISI 321 or the niobium bearing type 347 These additional elements are strong carbide-formers and they react with any free carbon to prevent chromium depletion An alternative approach favoured for room-temperature applications is to specify a low-carbon grade such as 304L or 316L, but as carbon is an austenite stabilizer these alloys are less stable at cryogenic temperatures. It is also worth noting that type 316 has a better corrosion-resistance, especially in marine atmospheres, due to its 2-3% molybdenum content

3.1 2. Fe-Cr-Ni-Mn-N Alloys

Strengths higher than those of the 300 series can be obtained from these steels as their increased manganese content raises the nitrogen solubility limit One particular material in this series, Nitronic 40, a 21Cr-6Ni-9Mn-0 4N alloy, was chosen for the construction of the Pathfinder 1 Model for the NTF and a 2 Dimensional airfoil manufactured by McDonell-Douglas for the NASA LaRC 0 3m TCT Some problems were encountered due to grain boundary sensitization created during fabrication, but in the 2D airfoil these were removed by heating to 1000 C and then quenching into liquid nitrogen to achieve a controlled and uniform cooling rate. Although the material was supposed to be 100% austenitic it was found to contain up to a few % delta ferrite, a body-centered-cubic phase of lower toughness than the parent metal Remedial heat-treatments were unable to remove this stable delta ferrite and caused unacceptable grain growth (Ref. 24) However, fracture toughness tests gave very high values at 77 K and, as the delta ferrite was aligned along the rolling axis and the span of the model wing was also in this direction, it was felt that the fracture toughness would be adequate to ensure safe operation in the NTF Nitronic 40 can be machined using conventional techniques but care has to be taken to ensure good cooling as the material work hardens easily and tools can rapidly loose their cutting edge. Availability of the material in the form of bars and plates of the required size can also be a problem which seems to be getting more severe

Other high manganese-high nitrogen alloys such as Nitronic 33 (18Cr-3Ni-13Mn-.2/ 4N), Nitronic 50 (22Cr-13Ni-5Mn- 2/.4N) and Carpenter 18-18 plus (18Cr-18Mn-1Mo-1Cu-1Si-0 5N) are generally considered to have toughnesses too low for safe cryogenic operation In the AISI 200 series of steels the high-manganese contents are used primarily to increase nitrogen solubility and hence strength. The earlier alloys had poor fracture toughness at cryogenic temperatures, but more recently a modified AISI 205 steel, nominal composition 18Mn-5Ni-16Cr-0 024C-0 22N, has been shown by Ogawa and Morris (Ref 17) to give yield strengths of 1200 Mpa and Charpy impact energies of 61 J in the as-rolled condition at 77 K However, these alloys are not yet easy to obtain, particularly in the product forms likely to be needed for model construction

3.1.3 A286

This precipitation hardened stainless steel has become one of the state-of-the-art materials for the construction of models for cryogenic wind tunnels and it has been used for a variety of 2 and 3 D models in the NASA LaRC 0.3-m TCT with considerable success A286 screws are frequently used to fasten together smaller components and in the following paper Dr. Young will discuss NASA LaRC experience with their use and the various locking systems that have been evaluated to prevent them from unscrewing under aerodynamic loading or cryogenic temperature cycling The alloy was not considered strong enough for use in Pathfinder 1 as its yield stress at 77 K is only about 830 MPa but more recently it has been used for the fabrication of a model of the space shuttle to be tested in the NTF. Its nominal composition is Fe-25Ni-14Cr-2 2Ti-1 5Mn-1 2Mo-0 3V-0 2Al--0 5Si and it is the titanium, vanadium and aluminium additions that precipitation-harden the material during heat-treatment The material is fully stable with respect to martensitic transformation both during cryocycling and deformation at cryogenic temperatures Machining is rather difficult due to the tendency of the material to work-harden rapidly and tool wear can be excessive. Furthermore the studies of stress-induced dimensional changes to be discussed in section 5 have shown that large surface stresses are produced even during rough machining It is a relatively expensive material and there are also often difficulties in obtaining it in the desired product forms due partially to the considerable use of the material for strategic, high-temperature applications

3 2 Martensitic and Semi-Austenitic Stainless Steels

3.2 1 AISI 600 Series

Among this class of material are a number of materials that have had long and successful histories in the fabrication of models for use in ambient and high temperature wind tunnels due to their ease of fabrication and ability to hold a high quality surface finish For these applications the materials were used in the fully-hardened condition but it was recognized that in this condition they would be too brittle for cryogenic applications. The H1150M heat-treatment was therefore used to bring the Charpy impact energy up to the required minimum of 25ft-lb, but, as noted earlier, this caused dimensional instability in a 15-5PH airfoil when the metastable austenite re-transformed to martensite during cryocycling. Similar problems have been found, or can reasonably be expected, to occur with 17-4PH, 17-7PH, Custom 450, AM 350, AM355, PH15-7Mo and PH14-8Mo and these materials are not recommended for cryogenic use

3.2 2 PH13-8Mo

The picture is, however, slightly different for PH13-8Mo. From a comparison of the contraction rates that occur during the various heat-treatments shown in Table 2 (Ref 8) for PH13-8Mo with those previously given for 15-5PH in Table 1, it is clear that austenite is reformed during the higher temperature heat-treatments It would, however, appear that this austenite is more stable than that formed in the other alloys in this series Perry and Jasper (Ref 11) comment as follows.

"(After) heat-treatment at the lowest ageing temperature, in this case 482 C (900 F), the microstructure is essentially completely martensitic As the aging temperature increases, so does the

amount of reformed austenite The H1150M condition (the softest for these steels) has a rather complex microstructure Heating to 760 C (1400 F) results in much of the martensite going into solution at that temperature Upon cooling to room temperature, some of the austenite is transformed into untempered martensite. The rest of the austenite remains as austenite and the balance is highly overaged martensite The 620 C (1150 F) ageing then ages the martensite that was formed as a result of cooling from 760 C (1400 F), together with some additional reformed austenite. Therefore, the final microstructure consists of highly overaged martensite, normal overaged martensite and reformed martensite which is completely thermally stable (authors underlining) This results in a heat-treated stainless steel with reasonably good impact strength at temperatures as low as 77 K (-320 F) "

Table 2· PH13-8Mo Stainless Steel Stability Data (Ref. 11)

Condition	77 K Charpy V Impact E (J)	Contraction H T.-R Temp. (%)	Cryocycle Stability	300 K UTS (MPa)	Structure
H950	2 7	0 04- 06	-	1551	martensitic
H1000	5 4	0.04- 06	-	1482	m/s
H1050	5.4	0 05- 08	good	1310	m/s
H1100	6 8	0 08- 12	-	1103	m/s
H1150	-	0 30	-	1000	m/s + aust
H1150M	41	0 35	reasonable	896	m/s + aust

In the H1150M condition PH13-8Mo has a yield strength of 1000 MPa at 77 K and Charpy V impact energies between 40-80 J (30-60 ft-lb) depending on the source of the data. It is therefore comparable to Nitronic 40 in its properties and its structure has been considered in so much detail because it has been used for the construction of the solid wing for Pathfinder 1 and the half-scale Pathfinder 1 model Nevertheless there have been indications that, although the "complete thermal stability" referred to above may be true in the context of conventional applications, the very high dimensional stability demanded of models for cryogenic wind tunnels might not be met by PH13-8Mo in the H1150M condition It was possible that deformation induced during machining might trigger off further transformation of austenite to martensite that could, in turn, create dimensional instability on cycling to cryogenic temperatures. The material was, therefore one of the first studied in the stepped specimen program to be described in section 4 Some evidence was, indeed, found for dimensional changes after 3 cryocycles into liquid nitrogen, but no further movement occurred as a result of further cryocycles, suggesting that the structure of the material had stabilized during the initial cryocycles Experience with the two model parts made for the NTF gives further confidence for the continued use of PH13-8Mo for cryogenic models, as both proved to be completely stable. Both had been thermally cycled to liquid nitrogen temperature at the semi-finished machining stage to allow transformation of any unstable austenite and it would appear that final finishing did not further destabilize the structure (Refs 27 & 28).

3 3 18 Nickel Maraging Steels

Although they do not have the favoured austenitic structure, this family of high-strength steels are strengthened by precipitation hardening of the soft, low-carbon martensite to form a stable microstructure which is not adversely affected by thermal cycling to cryogenic temperatures Furthermore they are readily machined in the annealed condition and there is very little dimensional change during the single step ageing heat-treatment which takes place at the relatively low temperature of 480 C (900 F). The higher strength members of the family have unacceptably low toughnesses for most cryogenic applications, but the lower strength 200 and 250 grades, are tough enough to find application in many high load-bearing applications in cryogenic wind tunnels. For example, the 250 grade is used for the construction of stings, while the 200 grade is the most widely used material for constructing models for the NTF At least eight models, or substantial parts thereof, have been constructed or are still under fabrication at present The 200 grade has a nominal composition (Fe,-17 / 19 Ni,-3 / 5.2 Co,-0 15 / 2 0 Ti,-0 05 / 0 2 Al,- 0 03 C,- 0 10 Mn,- 0 01P) Its yield strength is 1860 MPa at 77 K and it has a Charpy V notch impact strength in the region of 25-50 J (18-37 ft-lb) depending on the product form The increasing difficulty of obtaining reliable supplies of cobalt have let the major US supplier of 18 Nickel maraging steel to introduce a series of cobalt-free alloys and the 200 grade is currently under active evaluation for possible use in the fabrication of cryogenic wind tunnel models (Ref 10)

As noted earlier the low-temperature toughness, as indicated by the Charpy V notch impact energy at 77 K can fall below the 25 ft-lb minimum required for NTF operation in some product forms The grain-refinement program referred to in section 2.1 has shown that significant increases can be obtained in the toughness at 77 K The grain-refining process consists of multiple heating and cooling cycles between the austenite and the dual-phase austenite + ferrite region, followed by rapid cooling to reduce the grain size

3 4 Ferritic, Quenched and Tempered, and Grain-Refined Steels

In lecture 2, it was noted that the 9 Nickel steels are the only ferritic alloys considered suitable for use at 77 K and the main drive shaft for the NTF fan is made from a special grade of this alloy. The material has also been considered for use in model construction, but the more recently developed 12 Nickel alloy looks more promising. Furthermore, as both 9% and 12%Ni steels undergo a ferrite to austenite phase change they are therefore capable of grain-refinement by multi-stage heat-treatment.

3 4.1 9 Nickel Steels

Two grades of 9 Nickel steel are readily available· the double normalized and tempered A 353 and the quenched and tempered A 553 which has a slightly better toughness and about a 10% higher strength than the double normalized grade. Both grades are relatively easy to obtain, readily machined and welded, but there is no matching filler and austenitic nickel-based fillers have to be employed to give adequate strength Unfortunately, this leads to a miss-match in the expansion coefficients and potential problems

with thermal fatigue and stability Furthermore, the 9 Nickel steels are not very corrosion resistant and suitable coatings would need to be applied to protect the surface of a model.

3.4 2 12 Nickel Steels

Initial work by Stephens and Witzke (Ref. 21) at NASA Lewis Research Center has recently been extended by Rush (Ref 31) at NASA Langley Research Center. Two alloy compositions, Fe-12 Ni-0 5 Al and Fe-12 Ni-0 25 Ti, have been selected for further development and this will be discussed in detail by Dr Young Suffice it to say that, if the results of the experimental heats are reproduced in the larger production melts, these alloys appear to offer considerable potential for use in cryogenic models The initial data on strength and toughness of both alloys at 77 K has been included in Fig 2 and it can be seen than the 12 Ni-Al alloy in particular has a combination of strength and toughness which places it above the upper trend line for current materials

3 4 3 Quenched and Tempered Steels

The quenched and tempered 9Ni-4Co steels, particularly HP 9-4-20, have been used for 2 Dimensional models with some success. They have also been included in the grain refinement program and significant improvement in toughness at 77 K has been achieved However, there are reservations about its dimensional stability and its relatively poor corrosion resistance limits its potential usefulness

3 5 Aluminium Alloys

Aluminium alloys may be divided into two groups according to their basic metallurgical strengthening mechanisms: [1] the solution-hardened alloys which are very ductile but only of moderate strength unless cold-worked, and [2] the stronger, heat-treatable, precipitation-hardened alloys Type 5083 is probably the most widely used of the solution hardened alloys, due in part to its excellent weldability. Even in the as-welded condition its full strength is retained, thus giving it an advantage over the nominally stronger heat-treatable alloys if post-weld heat-treatment is not possible For example, alloy 6061 in the solution-treated-and-artificially aged T6 condition is stronger than that of 5083, but as-welded its strength drops below that of as-welded 5083. A series of six solids of revolution having the same size and shape as model bodies to be tested in the NTF have been made out of alloy 6061 in the T6 condition. Of the other heat-treatable alloys, the aluminium-copper 2014 and 2219 have been used in a number of aerospace cryogenic applications where their high strength to weight ratio is advantageous The toughness of the very high strength 7000 series alloys is, however, too low for most cryogenic purposes.

A number of cryogenic wind tunnel models, or parts thereof, have been built from aluminium alloys and operated successfully However, their elastic modulii and strengths are generally too low for their use in the more heavily-loaded components such as airfoils in pressurised tunnels such as the NTF Complications can also arise when aluminium and steel components are mixed in the same model, as the two materials have significantly different coefficients of thermal expansion. Nevertheless, aluminium alloys are easy to machine and readily weldable, although brazing and soldering are not easily carried out in model fabrication. The surfaces of models also need some form of protection to prevent them from being scratched

3 6 Titanium Alloys

Two titanium alloy have been used for cryogenic components, particularly in aerospace applications where their high strength to weight ratio is a distinct advantage The Ti-5Al-2 5Sn alloy has a stable h.c p structure and can be used down to 77 K, whereas the Ti-6Al-4V alloy has a duplex h c p / B c c. structure and is not used below 77 K because of excessive notch brittleness. For cryogenic use the special ELI (Extra Low Interstitial) grades have to be specified because the toughness of titanium is severely degraded by too many interstitial elements As these include carbon, nitrogen, oxygen and hydrogen, great care has to be taken during fabrication, particularly welding, to prevent their pick-up Furthermore, titanium alloys are not easy to machine, they are relatively expensive and for these reasons few, if any, models for cryogenic wind tunnels have yet been made in titanium alloys

3.7 Nickel Based Alloys

All nickel-based alloys have the austenitic structure that makes them suitable for cryogenic applications, but relatively few have, as yet, been used for model construction This is most probably due to a combination of their relatively high cost, poor availability and the considerable difficulties experiences in machining the high strength alloys such as the Inconels using conventional machining techniques. However, advances in chemical milling, electrical discharge machining, electron beam welding and other modern technologies have reopened the question of their possible application for model building. Nickel coatings have been used to rework model surfaces that have been undercut during machining or damaged in service, electroless nickel being used where hard finishes are required while electrolytic nickel is preferred if high ductility is needed. Nickel-copper alloys, Monels, have excellent corrosion resistance and have been used for cryogenic applications, but they do not posses any outstanding advantages that make them attractive for model building. The most promising alloys are the nickel-chromium Inconels, in particular the precipitation-hardened types 718 and X750 Inconel 718 has the higher yield strength, 1172 MPa at 300 K and 1342 MPa at 77 K, while X750 has a slightly lower strength but higher toughness

3.8 Copper Based Alloys

Copper based alloys have limited applications for cryogenic models and are used in those applications that make use of their good thermal and electrical conductivities, their availability, or the ease with which components can be machined and joined. Commercially pure copper is used for electrical conductors and is readily available Copper-zinc alloys, such as the 70Cu-30Zn alpha brasses and the bronzes, particularly phosphor, silicon and aluminium bronzes, tend to be used for small, lightly-loaded components that are easily machined from available product forms. Brasses are readily soldered or brazed,

although the temperatures involved in most brazing operations would anneal any cold-worked material. It is, however, the precipitation-hardened beryllium coppers that are possibly of most interest for model construction The relatively small amount of beryllium needed to form the precipitates that allow the room temperature yield strengths to reach 1000 MPa in the fully-hardened condition do not excessively degrade the high thermal conductivity of pure copper Beryllium copper is particularly useful in those circumstances where good thermal conductivity is needed to minimize cool-down time or temperature gradients and it is often used to form high-conductivity inserts to take heat away from particularly critical regions The main drawback of the material lies in its very low toughness at cryogenic temperatures in the fully-hardened condition. Nevertheless a 2 D beryllium copper airfoil has been made by the Douglas Company and tested successfully in the 0 3-m TCT at NASA LARC. (Ref 13)

4. STRESS-INDUCED DIMENSIONAL CHANGES IN METALLIC ALLOYS

4 1 Induced Stresses and their Effect on Dimensional Stability

Stress-induced deformation can produce dimensional changes of many thousandths of an inch on typical airfoil model sections. These stress systems can be of considerable magnitude and can originate from one or more of the following mechanisms

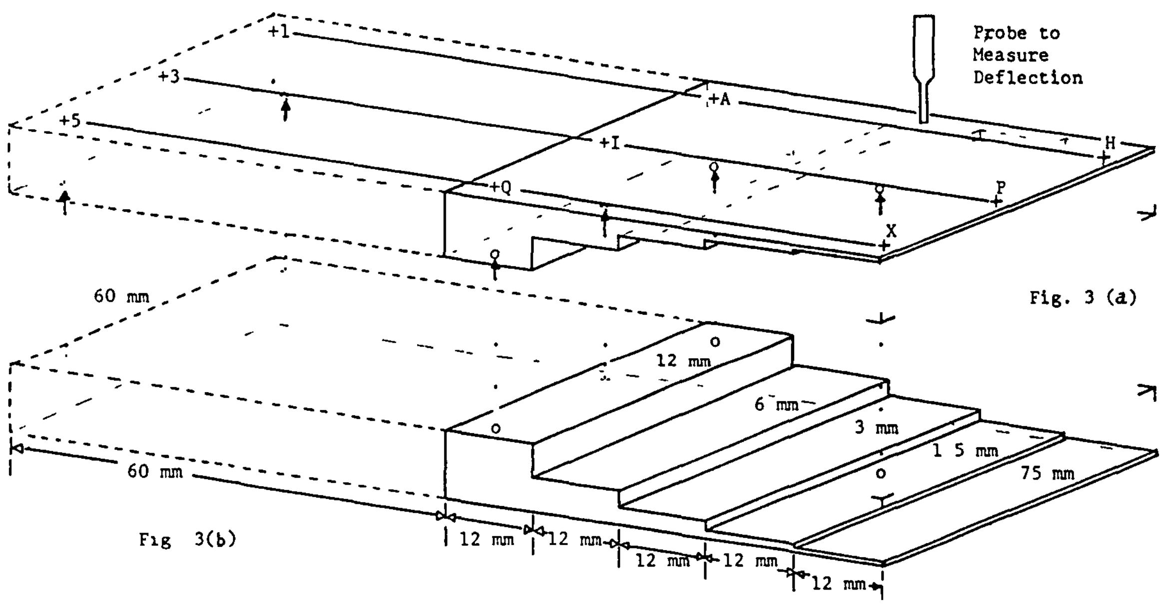
- unbalanced residual compressive and tensile stresses set-up during the original fabrication,
- quench-induced stresses generated on cooling from high temperature heat-treatments,
- compressive or tensile surface stresses induced by machining. These can be elastic or plastic depending on the degree of deformation created during mechanical working of the material and they can cause phase transformations in the surface layers,
- stresses created by temperature gradients, particularly across uneven sections

Many different configurations were used in the initial investigations, including fully profiled airfoils and wedge shaped specimens with thin, tapered trailing edges representative of typical airfoil models However, in view of the large number of possible combinations of material, machining technique, heat-treatment and other fabrication processes, a simplified, yet representative, stepped specimen configuration was adopted by NASA LaRC to allow these effects to be identified separated and quantified

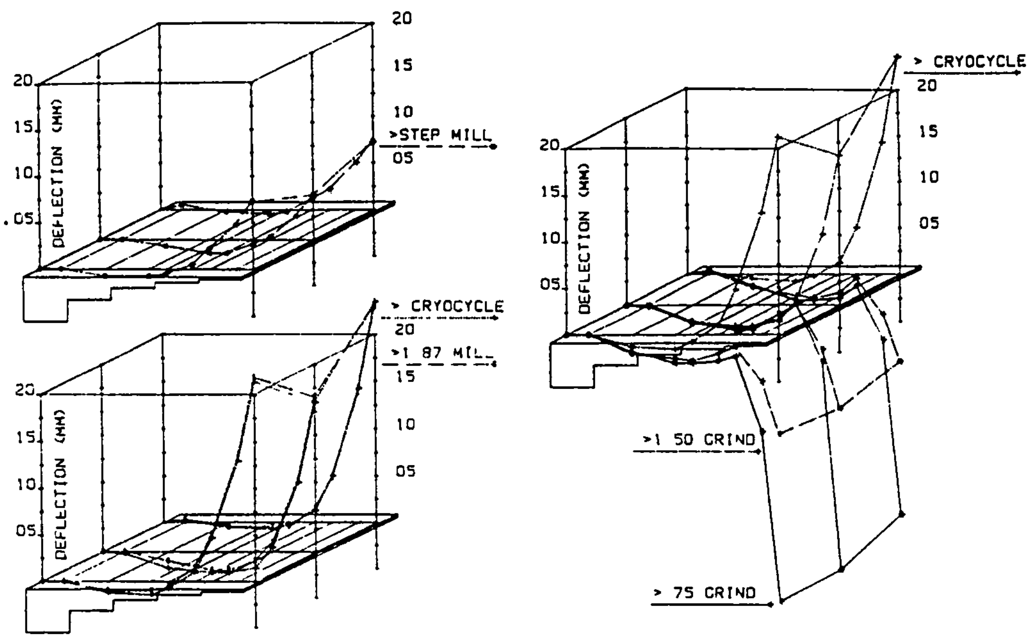
4 2 The Stepped Specimen Program

4 1 1 Specimen Configuration

The configuration used for the first 18 specimens of 18Ni 200 grade maraging steel, A286 and PH13-8 Mo stainless steel is illustrated in Fig 3(a) (Ref 26) By limiting the maximum thickness to 12 mm, it was possible to fabricate specimens from readily available 1/2 inch plate and the choice of 60 mm width and 60 mm length minimized the amount of material required. In its final form the specimen has five steps of length 12 mm and thickness 12, 6, 3, 1 5 and 0 75 mm, the thinnest giving the most sensitive region for observing the effects of fine finishing cuts. The flat underside of the specimen provides a firm support for machining operations carried out on the top surface. It also acted as the reference surface for subsequent validation measurements when the specimens were inverted and supported at the three points marked with o symbols in Fig 3(a). However, interpretation of the deflections of the reference surface were complicated by the fact that the 3rd support point lay within the machined region For the latest series of specimens the configuration was, therefore, modified to increase the length to 120 mm, as indicated by the dashed lines in Fig. 3 (a), and allow the three support points marked with ☆ symbols to be contained within the unmachined region (Ref 28)



Figures 3(a) and (b) Configurations of Original and Modified Stepped Specimens



Figures 4 (a), top left, (b), bottom left, and (c), right. Machining-Induced Deformation in A286

4 1.2 Initial Results and their Interpretation

Many different operations were carried out sequentially on each specimen in order to gather as much information as rapidly as possible Milling with ball-ended cutters was used to reproduce the type of stresses induced during initial shaping on multi-axis CNC machines, with grinding used to represent the finishing stages Feed rates, thickness of each cut and other machining details for each material were specified to be as used in actual model fabrication For the proof-of-concept specimen made from 18 nickel 200 grade maraging steel, continuous measurements of the machining-induced deflection were made along the three lines A-H, I-P and Q-X shown in Fig. 3 (b). After milling the reference surface was found to have an upward deflection, indicating that compressive stresses were created by milling the opposite face By treating the specimen as a cantilevered beam, it was possible to calculate the magnitude of these compressive surface stresses These were found to increase from 36 to 62 MPa (5 to 9 ksi) over the 4 milling cuts, each of depth 375 microns (0.015 in), used to reduce the thickness from 3 to 1 5 mm. Subsequently, 17 similar specimens of A286, PH13-8Mo and 200 grade maraging steel were put through a similar machining sequence Eight readings were taken along each of the three lines A-H, I-P and Q-X to give a total of 24 data points (Ref. 27)

The effect of of the different machining operations was followed by joining these points to reconstruct the appropriate reference surfaces as shown in Fig 4 (a) to (c) for an A286 specimen The surfaces shown are: (a) after milling the 6 and 3 mm steps, (b) after milling the 1 5 mm step and after cryocycling, (c) after cryocycling, after grinding the 1 00 mm step and after grinding the 0 75 mm step The reproducibility of the shape of the surfaces before and after cryocycling in Fig 4 (b) is an impressive confirmation of the excellent dimensional stability of A286 at cryogenic temperatures

4 1 3 Subsequent use of the Modified Specimen Configuration

The dip in the reference surfaces below the original reference plane in Figs 4 is a consequence of the location of the third support point in the machined area of the specimen. As noted earlier the modified specimen configuration avoided this problem and allowed easier interpretation of the surface deflections Improvement in the measuring technique also allowed over 360 data points to be gathered along each of the three lines 1 to H, 3 to P and 5 to X, thus effectively creating continuous traces This increased precision allowed dimensional stability during cryocycling to be studied in more detail. Fig 5 shows how a specimen of PH13-8Mo moves during initial cryocycling, but then remains completely stable during subsequent cryocycles This characteristic is exploited in practice by cryocycling models before finish machining to allow any necessary relaxation or phase transformation to take place before the model enters service (Ref 28)

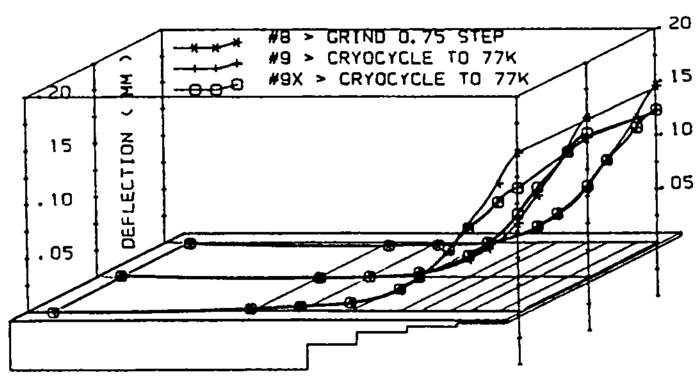


Figure 5. Machining-Induced Deformation in a PH 13-8Mo Specimen with the Modified Configuration

The very large deflections displayed after machining the thicker steps indicate that large surface stresses are created by work-hardening during milling and grinding, a confirmation of workshop experience that the material is difficult to machine. The common practice of machining opposite faces alternately does, however, tend to balance the surface stresses created on each side and thus prevent such large deflections occurring on an actual model The shapes of the surfaces in Fig 4(c) indicate that grinding sets up tensile surface stresses, as the sign of the deflections created during milling was reversed by grinding

It would, therefore, appear that if warpage occurs during rough machining of, for example, a 2 or 3 D airfoil, and if at least one surface is still over-size, dimensional fidelity could be restored by milling or grinding that surface to induce an appropriate balancing compressive or tensile surface stress

4 1 4. Future Program

It is envisaged that the next phase of the program will involve further in-depth study of the materials most likely to be used for the fabrication of cryogenic wind tunnel models, particularly the 200 grade maraging steels. Separate specimens will be used to measure the stresses created in different machining operations such as milling, grinding, lapping and hand-finishing, as well as the supposedly stress-free techniques such as EDM and chemical milling Stress-relieving heat-treatment cycles will also be investigated to determine their ability to remove machining-induced deformation. Scale effects will be studied using larger sized specimens, and stress-balancing investigated by developing techniques of validating specimens machined on both sides. (Ref. 29)

5 JOINING TECHNIQUES FOR METALS

Attainment of the optimum mechanical properties of materials at cryogenic temperatures requires careful control of their microstructure In particular, the desirable combination of high strength and adequate toughness is only attainable if the grain size can be kept small and the grain boundaries free from degradation by sensitisation Any joining technique that involves heat input must be evaluated carefully to ensure that neither the grains nor their boundaries are degraded during, or subsequent to, the joining process.

During conventional fusion welding enough heat has to be input to cause localised melting of the parent metal and this also causes annealing and modification of the adjacent heat-affected zone For almost all wind tunnel models, the heat inputs from welding processes such as MIG, TIG, SMAW, etc are too great and the resultant heat-affected zones too large for these processes to be acceptable However, in the case of electron beam and laser welding, heat inputs are so low and control of the heat-affected zone so good that these techniques are becoming indispensable for joining together sub components. For example, many airfoils are designed with cover plates that allow access to the centre of the airfoil for the passage of pressure tubing from the sensing orifices on the airfoil surface. Electron beam welding has been used on many airfoils to secure fully profiled coverplates to the rest of the airfoil without damaging the tubes or their joints. It is reported by Griffin (Ref 14) that laser welding without the use of fillers can produce strengths equal to that of the parent metal after heat-treatment The region affected is limited to a diameter of about 0 62 mm (025in) and a depth of between 0 5 and 1 2 mm (02 to 05 in) and is thus particularly useful for joining thin sections

Austenitic stainless steels such as the precipitation hardenable A286 and Nitronic 40 (21Cr-6Ni-9Mn-0 3N) can be brazed using nickel-based fillers such as the Ni-7Cr-3Fe-4 5Si-3 2B alloy (AWS4777B, BNi3) to give ductile joints with strengths similar to the parent metal yield strength These alloys, which are brazed at temperatures in the range 1010-1175 C (1850-2150 F), are of particular interest as they contain melting-point depressants such as boron and silicon which diffuse from the molten filler metal into the parent metal and cause the filler to solidify isothermally as the boron and silicon concentration drops They have been used successfully in a research program to develop a fabrication technique for the construction of 2 and 3 D airfoils by bonding together two or more flat plates containing pre-machined channels that subsequently become pressure passages in the bonded airfoil. Small samples have been produced without blocked channels or cross-leaks between them and current developments are concentrating on scaling up towards airfoils large enough for use in one or other of the NASA LaRC cryogenic tunnels For optimum bonds the gap between the two surfaces to be bonded, the faying surfaces, should be of the order of 0 025 to 0 05 mm (.001 to 002 in) and such dimensions are easy to maintain in small samples However, as warpage out of the plane of the plates tends to increase as the square of the plate diameter, this becomes increasingly more difficult in larger samples. A better understanding of the factors controlling dimensional stability, hopefully to be obtained as a result of the stepped specimen work described earlier, will be necessary before this technique can be used routinely for airfoil fabrication

During brazing enough heat has to be supplied to the components to allow the filler metal to flow, wet the faying surfaces and fill the gaps between them In general, the highest strength fillers melt at the highest temperatures and there is the greatest risk of causing grain growth when they are used It has already been noted that a special heat-treatment has been developed to reduce the grain size and thus improve the otherwise marginal cryogenic toughness of the 18 nickel 200 grade maraging steels intended for fabrication of models for the NTF. However, most of these models needed brazing and, as serious grain growth starts at temperatures above about 1000 C (1830 F) in these maraging steels, the AWS4777 type of fillers cannot therefore be utilised. Good results were, however, obtained in an experimental program using a newly developed 47Ni-47Pd-6Si alloy (Metglas MBF-1005X) and brazing temperatures in the range 900-965 C [1650-1770 F] (Ref. 31) Other maraging steel models have been brazed using the more established silver-copper alloys such as AWS BAG 3 (50Ag-15.5Cu-15 5Zn-16Cd-3Ni) which can be brazed at temperatures between 780 and 900 C (1435 to 1650 F) As the recommended solution annealing temperature for these maraging steels is about 815 C (1500 F), the two operations could be combined if so desired Ageing takes place at between 315 and 705 C (600 to 1300 F) and it has been suggested (Ref 14) that brazing and ageing could be combined in the same heat-treatment using an aluminium filler to produce a diffusion brazed bond However, initial experiments at 480 C (900 F) using pressures of 28 MPa (4 ksi) failed to produce consistent bonds with adequate strengths The instrumented wing of Pathfinder 1, which was fabricated in Nitronic 40 (21Cr-6Ni-9Mn-N) stainless steel, was brazed using an 82% Au - 18% Ni alloy melting at 955 C (1750 F)

The temperatures involved in brazing operations are often high enough to give partial or complete relief of residual stresses created during previous machining operations and, if these stresses are unevenly distributed, distortion can occur. In extreme cases cracks have been found to propagate during brazing, or subsequent cooling and the choice of heating and cooling temperature profiles is often difficult Ideally, rapid cooling is advisable through temperature ranges that cause microstructural degradation or unwanted ageing, with slower cooling through, or periods held at, those lower temperatures that allow some degree of stress relief.

One pre-requisite for successful brazing, or soldering, is the removal of oxide films and contamination that would otherwise prevent the molten filler from wetting the two surfaces and producing a good bond between them Thorough cleaning and degreasing is always essential and there are two principal methods of removing oxide films, the use of active fluxes, and vacuum or reducing atmospheres in furnace brazing. The main disadvantage of active fluxes is the need to ensure their complete removal after brazing in order to avoid subsequent corrosion In contrast, furnace brazing, particularly of stainless steels, gives a clean product but can cause microstructural degradation if post-brazing temperatures cannot be reduced rapidly It is in practice difficult to cool thick sections quickly enough through the critical temperature range in a vacuum furnace to prevent some sensitization

Soldering is used to create joints at much lower temperatures, usually below about 330 C (620 F) and at these temperatures there are rarely, if ever, problems with microstructural or dimensional changes Eutectic composition alloys are preferred where available as they freeze without going through a two-phase, pasty region that causes flow problems The bond strengths attainable are also lower and in some of the stronger tin-rich alloys, brittleness can be created by phase changes in the tin Bond strengths are strongly influenced by factors such as joint geometry and bond thickness, the highest strengths coming from the thinnest joints due to plastic constraint by the adjacent surfaces It is also highly advisable to match as closely as possible the expansion coefficients of the solder and the metals to be joined, which need not necessarily be the same materials. This minimises the risk of failure due to thermal fatigue should the model have to undergo many temperature cycles between ambient and its cryogenic operating temperatures The very low melting point alloys such as Woods metal (50Bi-25Pb-12 5Sn-12 5Cd) may have restricted use in tunnels such as the NTF where there is an operational requirement to withstand temperatures up to 95 C (200 F) as it melts between 62 and 70 C (144-156 F) However, their potential should not be overlooked for other applications where this restriction does not exist

6 NON-METALLIC MATERIALS

Current state-of-the-art practice favours the use of metals for the construction of models for cryogenic wind tunnels, especially those for operation in pressurised transonic tunnels where aerodynamic loads can be quite large. Nevertheless, non-metallic materials have important roles to play in the construction of less highly loaded components or models and for particular applications where metals are unsuitable. In general, plastic materials have lower densities, modulii and strengths and higher expansion coefficients than metals, but in many cases they are easier to fabricate. Ceramics and glasses are stronger and stiffer, but more brittle and best used for compressive loads Natural materials, particularly wood, are often overlooked, but they are cheap, readily available, easy to fabricate and possess a number of useful properties For example, balsa wood has a very low density ranging from 90 to 190 Kg/m^2, it is an excellent thermal insulator and has a reasonable compressive strength Finally, it is worth remembering that one of the first models tested in the NASA Langley 7 x 11 in low speed cryogenic tunnel was a simple sharp leading-edge 74 degree delta wing whose wings and fuselage were made from a single piece of mahogany. A reasonable finish was obtained by filling the wood and applying several coats of lacquer enamel and this combination stood up well to the cryogenic environment

6 1 Thermoplastics

These plastics materials have long chain molecular structures in which the chains are held together by weak secondary bonds The mechanical properties of the resultant material are highly temperature-dependent and below the glass transition temperature they are rigid and brittle Lightly cross-linked elastomers are only able to show elastomeric behavior at temperatures about 20 C above their glass transition, especially when loaded dynamically No thermoplastics have glass transitions below about 150 K, most are completely brittle at liquid nitrogen temperatures and it is only PTFE and related fluorocarbons that are of much use at low temperatures They are used for gaskets, seals ,bearings and similar applications, but unfortunately, thermoplastics have a viscoelastic nature and they are prone to creep and stress-relaxation Consequently they are often reinforced with fibres or powders to minimise cold flow, which also has the effect of reducing their otherwise large coefficients of thermal expansion to make them more nearly match those of the metals they are used with The low friction characteristics of PTFE are not adversely affected by low temperatures and, when mixed with graphite and bronze powder, it forms a very useful bearing material (Glacier DQ) Fluorocarbons are also LOX compatible and thus give no problems should they inadvertently be in an oxygen-rich environment.

Thermoplastics are rarely, if ever, used in thick sections as the combination of their low thermal conductivity and high thermal expansion makes them prone to thermal shock In the form of thin films and fibres, plastics such as mylar find uses as electrical and thermal insulators, while some thermoplastics are foamed for use as insulating materials. Probably more important, however, is their use as lacquers and adhesives, often combined with thermosetting resins For example, epoxy-nylon adhesives are stronger than unmodified epoxies

6.2 Thermosetting Resins

Fully cured thermosetting resins form a 3 dimensional cross-linked network structure whose mechanical properties are much less temperature sensitive and prone to creep and stress-relaxation than thermoplastics. If unfilled, they generally have very high contraction coefficients and are thus almost invariably modified unless to be used in thin layers as in surface coating lacquers Many of the fillers used to cover the heads of fasteners, to build up complex fairings and fillets and to fair up the surfaces of wind tunnel models, are loaded thermosetting resins The fillers are generally materials such as glass,

carbon and ceramic powders that have very small expansion coefficients and the composition is chosen so as to match that of the substrate material. The rule of mixtures:

expn co'ft mixture = (expn co'ft. filler x vol. % filler) + (expn co'ft resin x vol % resin)

can be used to give a good indication of the required composition, but experimental testing of a range of compositions that encompass to predicted value is usually necessary to optimize performance Results of NASA LaRC experience on filler materials will be given in the following paper by Dr Young

When blown to form a closed-cell foam, many thermosetting resins form excellent insulators and some foams are also rigid enough to bear reasonable compressive loading. For wind tunnel models, foams are sometimes used in the centre of body or airfoil segments, either to fill a void or as the rigid core of a composite structure with a bonded skin of fibre-reinforced plastic forming the stressed, aerodynamically profiled surface Probably the major uses of thermosetting resins are, however, as the matrices of the high-performance composites to be considered in the next section

6 3 High Performance Composites

For cryogenic applications virtually all high performance composites use epoxy resins for the matrix and glass, graphite or Kevlar fibre as reinforcement High specific strengths and modulii are obtainable using unidirectional reinforcement, while woven fibre cloths allow 2 dimensional stressed skin structures to be fabricated without too large a loss of performance compared to the unidirectional ideal Reinforcement in 3 dimensions does, however, result in a serious lowering of the mechanical properties The properties of a single layer of woven cloth are anisotropic, with maximum strengths and modulii along the warp and weft direction, but more isotropic properties can be obtained in laminates by varying the fibre orientations from layer to layer Alternatively the inherent anisotropy can be utilised to enhance the mechanical and/or thermal properties in chosen directions to meet specific design requirements

Glass fibre reinforced epoxy systems are by far the most widely used both at cryogenic and ambient temperatures where their high strengths and good toughness are desirable Their main drawback is in their low elastic modulii and the resultant large working strains High modulus graphite fibres can be partially or completely substituted for glass to produce stiffer composites, but their higher electrical conductivity can sometimes be a problem and even lead to galvanic corrosion if used in conjunction with more anodic metals such as aluminium A reasonable compromise is offered by the more recently developed polyimide fibres such as Kevlar 49 which have a 45% higher modulus, a 42% lower density and similar strengths when compared to glass. This laminating cloth has a low thermal conductivity and, for a thermoplastic, a relatively low coefficient of thermal expansion, which minimises problems of differential thermal contraction between the composite and metallic alloys Griffin (Ref 14) has fabricated and tested a replacement forward body section for an NTF model from Kevlar/epoxy in order to compare its mechanical and thermal characteristics with those of the 18Ni 200 grade maraging steel original Initial results appear favourable, the most serious problem involving differential thermal expansion between the dissimilar materials where the forward and main body sections join

A preimpregnated epoxy resin/E glass cloth system was used successfully for fabricating the fan blades for the NTF and details of the system and the tests used in its verification are given in a report by Klich et al (Ref 16) Two different types of cloth having different fibre densities in the warp and weft directions were used and stacked at varying orientations in the 19 ply thick laminate The same system has also been used at NASA LaRC to construct a 2 D airfoil for the 0.3-m TCT. The basic shape of the airfoil core was fabricated undersize, stainless steel pressure tubes were adhesive bonded into grooves machined in the core and further plies were then pressure molded over the tubes to create the required airfoil profile Pressure orifice holes were drilled through from the surface to pick up the buried tubes and a good surface finish was obtained by hand polishing. The airfoil was then tested safely and successfully in the 0.3-m TCT at cryogenic temperatures A similar system is also being considered for fabricating a replacement tail fin for the Pathfinder 1 NTF model

6 4 Glass and Ceramics

Although able to withstand reasonable compressive stresses, neither glasses nor ceramics are likely to find much application in the bulk form in cryogenic models as they are brittle when loaded in tension Pyrex glass and pyroceram do, however, have very low expansion coefficients which renders them almost immune from thermal shock and gives excellent dimensional stability Should windows or other optical components be needed on models, Pyrex would be the logical choice. When ground to a fine powder, advantage can be taken of their low expansion coefficients in using the powder as the filler to reduce the expansion of resins and thus make the mixture compatible with metals The use of E glass fibres for reinforcement has already been noted, but the growing use of optical fibres for communications might lead to their use for data transmission within or from a model.

The demands for higher thermal efficiencies in high temperature gas turbines and other engines had lead to considerable improvements in the strength and toughness of engineering ceramics based on oxides, carbides and nitrides While their low temperature properties are not yet outstanding, they are improving and it would be worth keeping their development under observation. For example, machinable ceramics might have applications for lightly loaded components where their low thermal expansion and dimensional stability might be advantageous Even state-of-the-art ceramics such as alumina could find use as bearings which can run against each other without lubrication and be stiffer than conventional metallic or polymeric systems.

7. CONCLUSIONS

Experience gained from the construction and testing of small models in the first generation of cryogenic wind tunnels, such as the 0.3m Transonic Cryogenic Tunnel at NASA LaRc, has given a valuable indication of suitable materials and fabrication techniques and highlighted some of the problems likely to be encountered Models for the larger tunnels such as the NTF pose an even greater challenge due principally to a combination of their increased size and higher operating stresses The required combination of high yield strength and adequate toughness at the lowest operating temperatures has severely

restricted the range of materials available Research and development work is being carried out on improved materials to increase the strength of inherently tough alloys and to increase the toughness of strong alloys

Earlier problems encountered with dimensional instability are now understood to have arisen due to microstructural instability in the material and the importance of choosing stable materials is now more widely understood However, most conventional machining techniques induce surface stresses, tensile from grinding and compressive from milling, which can be quite large in alloys like A286 that work-harden rapidly Dimensional changes can occur, particularly in thin or asymmetric sections if care is not taken to balance the surface stresses In most model shops opposite faces are machined alternately to minimise this problem Subsequent heat-treatment, for example as might be carried out to braze together sub-components, can upset the delicately balanced stresses and lead to warpage which could be serious enough to render the model unsuitable for testing. Furthermore, in the larger models, problems are likely to be more severe as dimensional changes, such as warpage of a wing tip, are likely to increase at least linearly with the span of the wing. The stepped specimen program has been set up to measure such dimensional changes as might be created by thermally cycling between room and cryogenic temperatures as well as to provide information on machining-induced deformation and the heat-treatments that might be used in its removal

The development of suitable, strong bonding and joining techniques is also an area where further progress is necessary In general, the strongest bonds are formed at the highest temperatures and in welding some of the parent metal is remelted into the fusion zone and the structure of the adjacent material in the heat-affected-zone is altered, often detrimentally Techniques such as laser and electron-beam welding have been found useful for joining small parts such as cover plates because of their low and localised heat inputs, but they are unsuitable for many larger applications. Brazing is the most commonly utilised technique for joining model components and the correct choice of filler is very important The highest strengths are obtained from the nickel-based alloys and they require high brazing temperatures While this may be acceptable for alloys such as A286 which can be subsequently heat-treated to achieve their optimum properties, problems are created with their use in materials such as the 18 nickel maraging steels These high-strength alloys must have a small grain size to ensure adequate toughness at 77 K and the grain growth that takes place at temperature above 1000 C (1800 F) would render them unsuitable for cryogenic operation Although conventional nickel-based alloys are thus unsuitable, the recently developed nickel-palladium alloys appear to offer a satisfactory alternative. The lower temperature silver solders have been used for most model brazing operations with relative success, although some problems have been encountered due to the creation or relief of stresses during brazing or subsequent cooling

Finally, it would appear that the use of high-performance composites such as the glass-, carbon- and Kevlar-reinforced epoxies may have an important part to play, particularly in the fabrication of the more lightly loaded parts of models Other non-metallic materials have small, but nonetheless important, roles as seals, thermal insulation, fillers, adhesives, etc. Aluminium alloys have been used for the fabrication of simple, lightly-stressed models and copper-based alloys including bronze and beryllium copper have been used for models as well as parts such as bearings All of these materials have different expansion coefficients and it is highly important to recognise the problems that can arise if they are used together Tight fits can become much looser or clearances can be reduced and binding take place if dissimilar materials are cooled from room to cryogenic temperatures. Large stresses can be set up by differential thermal contraction and these stresses can lead to distortion or even failure

It can therefore be claimed, with considerable justification, that the advances to be gained by the aerodynamicists in the attainment of high Reynolds numbers in cryogenic wind tunnels have had to be paid for in the complexity of the models to test in them. The challenges thus set to model designers and fabricators are being met and experience is accumulating on the best materials and techniques to utilize There is still, however, much work to be done and many problems to solve and it can confidently be predicted that if a third AGARD lecture series is held on Cryogenic Wind Tunnels in another five years time, models and materials and techniques of construction will again be a major part of the programme

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9 . ACKNOWLEDGEMENTS

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Table 1 Continued

Maraging, Ferritic and Martensitic Steels

18 Ni maraging	9 Nickel	9 Nickel	12 Nickel	12 Nickel	9 Ni-4Co- 2C	
300	A 353	A 553 type 1	0 25 Titanium	0 5 Aluminum	AMS-6523	1
9Co- 48Mo- 6Ti 18 5Ni- 03C	9Ni-0 1C-0 6Mn-0 25Si-0 01S 0 02P-0.05Al-0.05Ti		12-13Ni-0.05C- 17 to 26Ti- 025Cr-.01Si	12-13Ni-0 3C- 25 to .50Al- 025Cr- 01Si	9Ni-4 5Co- 2C 3Mn- 75Cr- 7Mo	2
martensitic	ferrite-mart'te	ferrite-mart'te	martensitic	martensitic	martensitic	3
fully aged	2x norm. & temp	Qu & temp	Qu & temp	Qu. & temp	Qu & temp.	4
ppt in low-C ms	tempered mart't + gr ref	tempered mart't	very fine grain	very fine grain	tempered mart't +gr ref	5
reasonable	bad	bad	reasonable	reasonable	poor	6
(t) (v)	(lng)	(t) (lng)	(bh)	(sw)	(rp) (r) (r)	
1903 1965	650	700 700	807		1275 1288 818	7
1982 2000	830	800 770	1076		1414 1385 1094	8
11	24	24	16		17 14 31 4	9
55 57		67	65		65 69 60 5	10
	(r) (r)	156 to 205	192		168	11
25 23	168 140 187	158			81 78 120	12
196 8 189 6	195	186			198 6	13
308	285	286 (g)			296	14
2344	930	1000 990	1255	1300	1497 1107	15
2475	1180	1180 1140	1407		1592 1549	16
	25	24	17		12 34.5	17
40		57	61		56 41	18
	(r) (r)	164 to 182	225	243	50	19
12	99 65 138	65			18 52	20
206 3	205	207				21
.303	.28	279 (g)				22
	470	-				23
-	11 4 (total contract'n of 9Ni					24
-	4.95 (from 300 to 77K = .19%)					25
25.3	29	28				26
	13	12.5				27
8 00					7 83	28
Air, Vacuum	Air	-			Air, Inert, Vac	29
1000 [1830]						30
815 [1500]	n/a	n/a			900,AC,816,WQ	31
1hr/in, AC	n/a	n/a			1 hr/in	32
480 [900]	899 788 586 AC	788,WQ;588,AC	685	550	550 [1025]	33
3 to 6 hr	1 hr/in	1 hr/in	2hr	2hr	4 to 8 hr, AC	34
001mm/mm		n/a				35
	temper embrittlement 370 to 540					36
	550 to 580				538 [1000]	37
excellent	(good)	-	(good)		?	38
(good)	(good)	-	-		poor	39
(excellent)	(good)	-	-		poor	40
(good)	-		-		?	41
good	good	-	(good)		difficult	42
good	good	-	(good)		good	43
good	good	-	(good)		reasonable	44
as 200 grade	GTA MIG SUBARC				TIG	45
"	excellent				good	46
"	?					47
"	?					48
"	?					49
8 to 10	3 to 4	3 to 4	research alloy	-	5 to 6	50
reasonable	good	good	not yet		limited	51
reasonable	good	good	available		limited	52
reasonable	good	good	commercially		limited	53
Toughness too low for most cryogenic uses	NTF fan shaft used special 9 Ni. Poor corosion resistance means model use unlikely		NASA developed alloy to combine high strength and toughness		limited use in 2D airfoils	54
(v) = Ref 10	(g) = Ref 14	(lng) = Ref 4	(t) = Ref 22	(r) = Ref 19	(rp) = Ref 9	55

- symbol signifies that the entry is the same as that in the previous column

TABLE 1 Properties of Alloys used in Model Construction

Stainless Steels

	Property / Material	18Cr-8Ni	18Cr-8Ni-N	18Cr-10Ni-2Mo	25Cr-20Ni
1	Grade	AISI 304L	AISI 304N	AISI 316	AISI 310
2	Composition	18/20Cr-8/10Ni-2Mn-.03C-1Si-.03S-.04P	18/20Cr-8/10Ni-2Mn- 08C- 1/ 16N 1Si-.03S- 04P	16/18Cr-10/14Ni-2Mn- 08C-2/3Mo-1Si- 03S- 04P	24/26Cr-19/22Ni-2Mn- 25C-1.5Si-.03S- 04P
3	Structure	metastable aust.	stable ? aust.	metastable aust	stable aust
4	Condition	annealed	annealed	annealed	75% cold rolled
5	Strengthening Mechanisms	solution	solution + N2	solution	solution + C R
6	Corrosion Resistance	excellent	excellent	excellent	excellent
	300K MECHANICAL PROPERTIES	(w/lng) (t)	(w/lng)	(p&b))	(w/lng)
7	Yield (MPa)	241	315	234	470
8	U.T.S (MPa)	641	590	584	650
9	Elong (%)	65	51	60	35
10	Reduction in Area (%)	83	75	77	
11	Kc (MPa√m)	430	340	400	
12	Charpy V (J)	217	336	169	
13	E (GPa)	200 190	(200)	195	191
14	Poissons ratio	289	289	294	305
	77K MECHANICAL PROPERTIES				
15	Yield (MPa)	427	700	445	800
16	U T S. (MPa)	1600	1557	1360	1210
17	Elong (%)	46	47	56	56
18	Reduction in Area (%)	71	63	67	
19	Kc (MPa√m)	400	330	166	
20	Charpy V (J)	190	200	154	
21	E (GPa)	214 205	214	209	205
22	Poissons ratio	278	278	.283	295
	PHYSICAL PROPERTIES				
23	Sp Ht (J/kg C) [77K]	480 [220]	-	-	400 [200]
24	Exp Co'ft @ 300K (106/K)	15 9	(total linear contraction of all 4 grades of stainless steel		
25	Exp Co'ft @ 77K (106/K)	13	(between 300 and 77K is 285 percent)		
26	Therm Cond 300K (w/m K)	14 16	14	14	11
27	Therm Cond. 77K (W/m K)	8 8 2	8	8	6
28	Density (g/cc)	8 00(p&b)	8.00	8 00	8.00
	HEAT-TREATMENT INFORMATION				
29	Atmosphere	Air, Inert, Vac.	-	-	-
30	Grain Growth (C) [F]	(1120 [2050])	--	-	(1136 [2080])
31	Soln Anneal (C) [F]	1010/1120 [1850/2050]		-	1036/1149 [1900+]
32	" " Time (hr)	(few hours)	-	-	-
33	Heat-Treatm't (C) [F]	n/a	-	-	-
34	" " Time (hr)	n/a	-	-	-
35	" Contraction (%)	n/a	-	-	-
36	Sensitization (C) [F]	550 to 930C	-	-	-
37	Stress relief (C) [F]	480 [900];slow cool. or 950 [1750]; rapid quench			-
	DIMENSIONAL STABILITY				
38	Metallurgical	poor, (Ms=230K)	good, (Ms=100K)	medium, (Ms=160K)	exc , (Ms=30K)
39	Cryocycle (Initial)	(good?)	(very good)	(good)	(excellent)
40	Cryocycle (Subsequent)	(very good)	(excellent)	(very good)	(excellent)
41	Machining	poor, (Md =400K)	good, (Md=250K)	medium, (Md=300K)	exc (Md=200K)
	FABRICATION				
42	Milling	poor	-	-	-
43	Grinding	poor	-	-	-
44	Surface Finish	reasonable	-	-	-
	JOINING/FINISHING				
45	Welding Process	MIG, TIG, SMAW	-	-	-
46	Weldability	excellent	-	-	-
47	Brazing Process	Vacuum or Inert Gas			
48	Brazability Alloy	AWS BAG 1,3 AWS BNi 3			
49	Solderability	Good with reactive flux, for example orthophosphoric acid.			
	COST & AVAILABILITY				
50	Cost ($/lb)	4	5	4	6
51	Availability Bar	excellent	good	excellent	good
52	" Plate	excellent	good	excellent	good
53	" Sheet	excellent	good	good	good
54	Comments	300 series stainless steels widely used for cryogenic tunnel fabric'n. Have been used for lightly stressed cryogenic models but too weak for higher loads in pressurised tunnels such as NTF			
55	Data References	w = Ref 2	(p&b) = Ref 11	(lng) = Ref 4	

Footnotes: Comments in () brackets are authors "best guesses" where data is unavailable or unquantified

Table 1 Continued

Stainless Steels

21Cr-6Ni-9Mn	25Cr-13Ni-.4N	A286	PH13-8Mo	15-5PH	17-4PH	
Nitronic 40	JAERI YUS 170	AMS-5736A	UNS S13800	UNS S15500	UNS S17400	1
21Cr-6Ni-9Mn-15/ 4N-.3V-1Si 08C- 03S- 06P	25Cr-13Ni- 40N-8Mo- 5Mn- 9Si-02C- 03P- 002S	25Ni-14Cr-2 2Ti 1 2Mo-1.5Mn- 3V .08C- 2Al- 5Si	13Cr-8Ni-.04C-1 1Al-2 2Mo-.03Mn- 03Si	15Cr-4 5Ni- 04C 3 4Cu- 4Si- 3Mn 25Nb	16 5Cr-4Ni- 04C 3 4Cu- 6Si- 3Mn .25Nb	2
stable? aust	stable? aust	stable aust	martste + aust	ms + rev aust	ms. + rev aust	3
annealed	annealed	STA	H 1150 M	H 1150M	H 1150 M	4
solutes + N2	solutes + N2	precipitates	ppt.+ temp ms.	ppt + temp. ms	ppt + temp ms	5
excellent	excellent	excellent	excellent	excellent	excellent	6
(a) (h)	(sak)	(t) (rp) (h)	(a) (h)	(a)	(a)	
400 483	460	750 690 689	586 586	717	586	7
710 758	861	1000 1103	896 896	896	862	8
50	52	24	22	23	22	9
70	75	37	70	75	68	10
		114/161 132	165			11
294 271	477	(g) 75	162 109	136	135	12
197		195 8 200.6	172	196	201	13
285		330 .306	278	.272	291	14
		(t)				
1034 1034	1131	930 827	1000	1007		15
1400 1379	1693	1482	1207	1386		16
	46			27		17
24	63			65		18
182		121				19
87 88	243	68	81	27	7	20
		202 7 (g)				21
						22
				418	460	23
16 7		16 7	10 9	11	11	24
		12 2(g)				25
13 4		14.9	12 7	17.9	(15)	26
(5)						27
7 83		7 96	7.76	7 82	7 82	28
Air, Vac, Inert	-	-	-	-	-	29
1180 [2150]		(1180 [2150])	(1180 [2150])	1180 [2150]	1200 [2200]	30
1066 [1950]		982 [1800]	927 [1700]	1030 [1900]	1030 [1900]	31
1 hr/in, + W Q		1 hr then W.Q.	30 min + A C	30 min. + A C.	30 min + A.C	32
not relevant		734 [1350]	760,AC; 620,AC	760,AC, 620,AC	760,AC, 620,AC.	33
" "		16 hr then A C	2 hr , 4 hr	2 hr , 4 hr	2 hr , 4 hr	34
			.0035	0024	(002- 003)	35
590/930 [1100/1700]		(- ?)	(- ?)	(- ?)	(- ?)	36
480[900],AC or	950[1750],WQ	Solution anneal then re-age		-	-	37
Stable		Stable	Stable ?	Unstable	Unstable	38
Good		Excellent	Some warpage	Large warpage	Large warpage	39
Excellent		Excellent	Excellent	Further warpage	Further warpage	40
High stress		V. High stress	Moderate stress	?	?	41
poor		bad	harder than 304	like 304	like 304SS	42
poor		poor	good	" "	" "	43
soft		reasonable	Very good	Excellent	Excellent	44
MIG, TIG, SMAW	-	- weld in	TIG	MIG, TIG, SMAW	-	45
Good	-	soln treat cond	Good	Good	-	46
Vacuum, Inert Gas		-	-	-	-	47
AWS BAg 1,3, AWS BNi 3,		soln. HT; reage	-	-	-	48
Good with reactive flux, for example orthophosphoric acid				-	-	49
5		9	7	7	7	50
Difficult	?	Long lead time	Long lead time	Reasonable	Reasonable	51
Difficult	Up to 60mm	"	"	"	"	52
Reasonable	Down to 0 3mm	Reasonable	"	"	"	53
Used for Path-finder 1 and other NTF models	Alloy developed in JAERI fusion research prog	Many 2 & 3 D models used in La RC 0.3m and NTF tunnels	Alloy must be cooled 16 [60] before ageing NTF model use	Alloys must be cooled 32 [90] before aging to complete martensite transformation Unstable in H1150M, too brittle fully aged		54
(a) = Ref. 8	(sak) = Ref 20	(rp) = Ref 9	(t) = Ref 22	(h) = Ref 15	(g) = Ref 14	55

- symbol signifies that the entry is the same as that in the previous column

TABLE 1 Properties of Alloys used in Model Construction

Aluminium and Copper Alloys

	Property / Material	Aluminum	Aluminum	Aluminum	Beryllium Copper
1	Grade	AAA5083	AAA6061	AAA 2014	
2	Composition	4 5Mg- 6Mn	1Mg-.6Si- 27Cu- 25Cr	4 4Cu- 8Si- 8Mn- 4Mg	1 8Be- 2Co- 1Fe- 1Si
3	Structure	f c.c	f c c	f.c c	f c c
4	Condition	annealed	T6	T6	soln HT & aged
5	Strengthening Mechanisms	solution	precipitation	precipitation	precipitation
6	Corrosion Resistance	good	good	good	good
	300K MECHANICAL PROPERTIES	(lng)(ml3)(asm)	(lng)(m63)(asm)	(lng)(ml3)(asm)	(m63)
7	Yield (MPa)	150	270	420	667
8	U T S (MPa)	313	306	476	702
9	Elong (%)	23	18	13	19
10	Reduction in Area (%)	35	56		68
11	Kc (MPa m)				
12	Charpy V (J)		22		51(U)
13	E (GPa)	71 6	70.2	73 1	131
14	Poissons ratio	.3334	3383		
	77K MECHANICAL PROPERTIES				
15	Yield (MPa)	164	330	470	819
16	U T S (MPa)	434	412	565	909
17	Elong (%)	33	24 5	14	31
18	Reduction in Area (%)	38	51		66
19	Kc (MPa m)				47(U)
20	Charpy V (J)		22		
21	E (GPa)	80 2	77 1		
22	Poissons ratio	3195	3277		
	PHYSICAL PROPERTIES				
23	Sp Ht (J/kg K) [77]	966 [340]	966 [340]	966	420
24	Exp Co'ft @ 300K (106/K)	23.2 23 4	23 2 23.4	23	17 8
25	Exp. Co'ft @ 77K (106/K)	9 0	9 0	•	
26	Therm Cond. 300K (w/m.K)	115 118	193	218	84
27	Therm Cond 77K (W/m.K)	55			
28	Density	2.66	2 7	2.8	8 23
	HEAT-TREATMENT INFORMATION				
29	Atmosphere				
30	Grain Growth (C) [F]				
31	Soln Anneal (C) [F]			496/507 [925/945]	
32	" " Time (hr)			1 hr (salt), air	
33	Heat-Treatm't (C) [F]			168/174 [335/345]	
34	" " Time (hr)			8 to 12 hr	
35	" Contraction (%)		none?	-	2
36	Sensitization (C) [F]	Aluminium alloys do not sensitise		-	
37	Stress Relief (C) [F]			360/412 [650/775]	
	DIMENSIONAL STABILITY				
38	Metallurgical	Excellent	Excellent	Good	Good
39	Cryocycle (Initial)	Good	Good	Good	Good
40	Cryocycle (Subsequent)	Good	Good	Good	(good?)
41	Machining	Aluminium alloys similar to 300 series stainless			(good?)
	FABRICATION				
42	Milling	Poor	Fair	Good	Poor
43	Grinding	Aluminium alloys not normally ground			?
44	Surface Finish	Poor	Fair	Good	Fair
	JOINING/FINISHING				
45	Welding Process	MIG, TIG, SMAW,	-	-	MIG, TIG,
46	Weldability	Good	Good	Fair	Excellent
47	Brazing Process	Not normally recommended for aluminium alloys			Furnace, torch
48	Brazability Alloy	"	"	"	Good, Ag-based
49	Solderability	Very agressive fluxes needed, not recommended			Excellent
	COST & AVAILABILITY				
50	Cost ($/lb)	2-3 $/lb	-	-	5-6 $/lb
51	Availability Bar	Good	Good	Good	Reasonable
52	" Plate	Good	Good	Good	Reasonable
53	" Sheet	Good	Good	Good	Reasonable
54	Comments	Used in bulk in tankage Limited model usage	Used for lightly loaded models in 0 3-m TCT & NTF	Stronger but lower toughness limits model use	Used for high thermal conductivity inserts
55	Data References	(lng) = Ref 4	(ml3) = Ref 6	(asm) = Ref. 5	(m63) = Ref 7

Footnotes· Comments in () brackets are authors "best guesses" where data is unavailable or unquantified

Table 1 Continued

Titanium, Low Expansion and Nickel Superalloys

Ti-6Al-4V	Ti-5Al-2.5Sn	Invar	Ni-Span C	Inconel 718	Inconel X750	
Ti-6Al-4V,ELI	Ti-5Al-2.5Sn,ELI	Nilo36, Nilvar	Constant Modulus 42			1
6Al-4V- 1Fe- 01C	5Al-2 5Sn- 2Fe- .07C	36Ni- 1C- 36Si- 35Mn-.1Al- 015P- 015S	42Ni-5 2Cr- 5Al 2 4Ti- .06C	19Cr-18.5Fe-3Mo 9Ti-5.1Nb & Ta	15 5Cr-7Fe- 7Al 2 5Ti- 95 Nb & Ta	2
h c p /b c c	h.c p	f c c	f c c.	f.c c.	f c c	3
Annealed	Annealed	Annealed	Soln HT & aged	Soln.HT & aged	Soln.HT & aged	4
Solute /2 phase	Solution	Solution	Precipitation	Precipitation	Precipitation	5
Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	6
(g) (n) (h)	(h) (n) (t)	(lng) (h) (t)	(m63) (asm)	(t) (h) (asm)	(h) (asm)	
951 896	724 875	276 289	774 793	1172 1034	758	7
1024 931	827 925	552 552	1202 1240	1404 1276	1241	8
17	19	55	24 18	20		9
47	44		50			10
96 9 100 (t) 90	90 101			90		11
27 37 27	34 24 34(g)	298	24 (U)	27	47 5	12
110 3 111	111	153 152	182	213	213	13
.330	(330)	2845				14
1576 1310	1207 1380	621 620	905	1207	862	15
1624 1413	1241 1437	862 862	1550	1620	1482	16
10	14	42	31.6			17
41	30		47			18
59 61 (t) 61	72 75			110	110	19
14 21 14	14 15 14(g)	68	23 (U)	27	47 5	20
121 4	(121 4)	140.4 141		227	227	21
		307 (asm)				22
(530) ([200])	530 ([200])	517 ([190])		(450 [170])		23
(9 3)	9 36 8.4/9.4	1 2 2 5		11 5		24
		0 4 83				25
(8.17)	8 17	13 8 13 8		0.1 to	0 23	26
(4.4)	4 4	6 2 6.2		.058 to	0 16	27
4.43	4 46	8.0		(8 2)	8 3	28
Vacuum, Inert Gas		Reducing/inert atmosphere		Inert, Air	-	29
ph tr T = 1000	760 [1400]					30
843/954 [1550]	815 [1500]	750/850 [1380]	(- ?)	980, A.C	980, A C	31
15/30 min;W Q	30 mins	30 min/in; W.Q.	(- ?)	1 hr	1 hr	32
480/540 [900]	n/a	315 95	650 730	720,FC; 620,AC	870,ac, 705,AC	33
4/8 hr, A C	n/a	1hr,AC, 48hr,AC	5 hr 3 hr	8 hr ; 20 hr	25 hr ;20 hr	34
n/a	n/a	n/a		0.09%	0 09%	35
do not sensitise		do not sensitise	-	Do not sensitise		36
704/829;1-2 hr	540/650,1-2 hr	same as heat-treatment		870 for 3 hr to 980 for 7/15 min		37
(stable)	stable	stable	stable	stable	-	38
(good)	(good)	(-)	(-)	(stable)	-	39
(good)	(good)	(-)	(-)	(")	-	40
						41
difficult	difficult	(like 304?)	(poor)	difficult, work hardens rapidly		42
fine,dry swarf is inflamable '		(" " ?)	(reasonable)	reasonable		43
poor ?	poor ?	Reasonable ?	(" ")	easily scratched		44
MIG, TIG, EBW	-	MIG, TIG	- ?	TIG, MIG, SMAW,	-	45
Excellent	-	good	- ?	good	-	46
Vacuum, Inert Gas		?	- ?	Vac, Inert, Air	-	47
Care needed	-	?	- ?	Copper alloys prefered to silver		48
not usual	-	active flux	- ?	Acid flux for Pb & Sn solders		49
6 to 9 depending on product form		9	10	12	- 12	50
reasonable	-	reasonable	poor	difficult	-	51
reasonable	-	"	"	not available	-	52
good	-	"	"	difficult	-	53
Poor low temperature toughness and difficult machinability combine to make titanium unattractive for cryogenic models		Total contraction from 300 to 77K =0 05%, 10% of steels	Used in springs & bellows, too brittle for general use.	High cost and extreme difficulty in machining, drilling and fabrication restrictusage to high temperature models		54
(n) = Ref 6	(g) = Ref 14	(t) = Ref 22	(asm) = Ref 5	(m63) = Ref 7		55

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15 Supplementary Notes

Langley Technical Monitor: Dr. Clarence P. Young, Jr.

16 Abstract

The problems confronting the designer of models for cryogenic wind tunnel models are discussed with particular reference to the difficulties in obtaining appropriate data on the mechanical and physical properties of candidate materials and their fabrication technologies. The relationship between strength and toughness of alloys is discussed in the context of maximizing both and avoiding the problem of dimensional and microstructural instability. All major classes of materials used in model construction are considered in some detail and in the Appendix selected numerical data is given for the most relevant materials. The stepped-specimen program to investigate stress-induced dimensional changes in alloys is discussed in detail together with interpretation of the initial results. The methods used to bond model components are considered with particular reference to the selection of filler alloys and temperature cycles to avoid microstructural degradation and loss of mechanical properties.

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